as moisture ingress into concrete are the two necessary prerequisites for almost ev expansive phenomenon, such as freezing and thawing, corrosion of reinforcing ste and swelling of alkali-silicate gels.

Specifications and Testing Methods for Sulfate Resistance

As will be discussed here, the absence of a conclusive hypothesis on t mechanisms by which concrete deteriorates from long-term sulfate exposure h prevented the development of appropriate acceptance tests and specifications f sulfate resistance. Since it is easier from laboratory tests to prove a direct correlati between the C_3A content of a portland cement and expansion in mortar prisms expos to a sulfate solution, most of the specifications and test methods have ignored the lo of strength and elastic modulus which are also associated with the sulfate atta During the early part of this century sulfate resisting portland cements, with low-C content (0-5% C_3A), were developed in several countries, such as by Ferrari in It and by Fleming in Canada. In 1940, ASTM C 150--the Standard Specification f Portland Cement--approved a sulfate resisting cement which is required to contain le than 5% C_3A. Since mortar prisms made with the sulfate resisting portland cem show a little or no expansion on immersion in a dilute sulfate solution for peri ranging from several weeks to several months, this approach has become the basis specifications and acceptance tests for sulfate resistance.

For a laboratory test to be really meaningful, the following criteria ought to satisfied: (a) it should yield reliable and reproducible information within a relati short time (e.g., 4 weeks or less) if the test is to be of practical value to a cem manufacturer or user; (b) it should correlate well with the field experience, i.e. sho reproduce as accurately as possible the mechanisms by which the sulfates attack cement hydration products; (c) it should be applicable to both portland and blen portland cements since both cement types are commonly specified for use un conditions of sulfate attack.

Early experiments showed that mortar bar expansions in sulfate solut depended greatly on permeability, therefore the use of graded sand, high water/cem ratio, and low cement content was favored for the purpose of accelerating the t needed for sulfate expansion. For instance, Thorvaldsen et al[4] developed a met according to which 1.55 by 1.55 by 10-cm mortar prisms, containing 20-30 mesh s with 1:10 cement-sand ratio, cured for 3-8 weeks, were exposed to a sulfate solu and the time required to show a given amount of expansion was measured. Based the results of a long-term laboratory investigation by the authors, the relative resista of some synthetic mixtures of portland cement compounds to solutions contai 1.8% $MgSO_4$, 2.1% Na_2SO_4, and a saturated $CaSO_4$ solution, is shown in Table 1.

From the data in Table 1, it should be noted that the $MgSO_4$ solution was fou be more aggressive than the Na_2SO_4 solution due to the former's pH lowering pote (associated with the chemical reaction involving decomposition of calcium hydro and precipitation of brucite and gypsum). Therefore, for application to those

conditions where the pH lowering phenomenon is not involved during sulfate attack, the use of a Na_2SO_4 or a $CaSO_4$ solution is more valid. In the Na_2SO_4 and $CaSO_4$ solutions, the two cements with no C_3A took a long time to register expansion. However, with the C_3S-C_2S cement a very rapid expansion was recorded after 12 years of exposure in the Na_2SO_4 solution. This expansion was probably preceded by slow transformation of calcium hydroxide and C-S-H to gypsum, and a corresponding loss in stiffness. The high C_3A cement responded rapidly to the sulfate expansion phenomenon in all three test solutions.

The ASTM Type I portland cements usually contain 8 to 12% C_3A and, therefore, take many months to show significant expansions in dilute sulfate solutions. Wolochow[28] used 1:4 cement-to-sand mortars, cured for 7 days, and exposed them to a 5% Na_2SO_4 solution. The results from an interlaboratory testing program showed that a 28-days immersion period was sufficient to detect portland cements of low resistance to sulfate attack. Since the reproducibility between different laboratories was not satisfactory, and since it was found difficult to agree upon a permissible expansion limit between the laboratory test results and the field behavior, the test did not become popular.

In immersion tests, considerable time is lost before the sulfate solution is able to permeate into the interior of a mortar or concrete specimen. In 1960, an accelerated test procedure was adopted by ASTM (Standard Test Method C 452) according to which the 14-day expansion is measured on 25 by 25 by 285 mm, water-cured mortar bars made from a mixture of portland cement and added gypsum, such that the total SO_3 content of the mixture before the hydration is 7%. The method does what it is supposed to do, i.e., in a relatively short period of 14 days it is successful in differentiating between the high-C_3A and the low-C_3A portland cements by accelerating the expansion associated with the ettringite formation. However, it does not simulate the field exposure conditions typical of the sulfate attack. **Instead of chemical interaction between an external sulfate solution and the hydrated constituents of cement paste, this method involves chemical interaction between anhydrous cement compounds and an internally incorporated source of sulfate ions.** Thus, the method is unsuitable for testing blended portland cements because, compared to ordinary portland cement, the blended cements have to be well hydrated before they develop sulfate resisting characteristics. Even for evaluation of the sulfate resistance of neat portland cements, the method has a limited value because it is much easier to determine the relative C_3A content of a portland cement by other ways than by this procedure. More importantly, it fails to take into consideration that the long-term deterioration of concrete by sulfate exposure involves not only the sulfate expansion phenomenon associated with the ettringite formation but also the loss of adhesion and strength associated with the formation of gypsum from CH and C-S-H.

The motivation to develop a relevant test procedure resulted in studies which culminated in a new ASTM Standard Method for Length Change of Hydraulic Cement Mortars Exposed to a Sulfate Solution, ASTM C 1012. Based essentially on Wolochow's[28] sulfate immersion test for expansion of mortar prisms, the procedure

involves making a mortar mixture (1:2.75 cement-sand ratio, 0.485 water/cementitious ratio), molding 25 by 25 by 285 mm specimens, curing the specimens in warm water (35°C) for 24 hours before demolding, subsequently curing them in saturated lime water at 23°C until such time that a mean compressive strength of approximately 20 MPa or more has been achieved, and then immersing the prisms in a standard sulfate solution for a period of six months. The immersion solution consists of 0.352 mol or 50 g/liter of Na_2SO_4. Alternatively, a mixture of 0.176 mol/liter of each of sodium and magnesium sulfates may be used.

The ASTM C 1012 Test Method is found suitable for both portland and blended portland cements. According to the ASTM C 595-89, Standard Specification for Blended Hydraulic Cements, the criterion for failure in the ASTM C 1012 is 0.1% expansion. Test data reported by Mather[29] showed that a portland cement with 9.4% C_3A took more than 5 months to reach 0.1% expansion. Using nine different fly ashes, the portland-fly ash cements containing 30% fly ash showed that five of the cements failed to meet the specification limit (0.1% expansion) in 6 months of sulfate exposure; however the four cements which met the specification time in 6 months immersion thereafter continued to show significant expansion (Fig. 1). Therefore, the long time to get the results is one of the shortcomings of this test. Also, no attempt is made to evaluate the loss of stiffness and strength from sulfate attack. This is indicated in the Figure by the continued expansions beyond the 180-day test period. After 202 days of sulfate immersion, a blended cement containing 30% of a Class F fly ash (Fly Ash No. 511) reached the failure criteria (0.1% expansion), and thereafter continued to show considerable expansion. This is inconsistent with the general field experience with Class F fly ashes and, therefore, both the validity of the test method and the specification are subject to question.

Instead of measuring expansion for sulfate attack, several researchers have developed procedures based on determination of strength loss. Koch and Steinegger used 1 by 1 by 6-cm mortar prisms (1:4 cement-sand ratio), cured in water for 21 days and subsequently immersed in a Na_2SO_4 solution containing 2.5% SO_3. The relative sulfate resistance of a cement is assessed from changes in the flexural strength at different ages up to 77 days of sulfate immersion. Markestad[31] reported pronounced changes in the compressive strength of high-C_3A portland cement mortar cubes (12.5 mm, 1:3 cement-sand ratio), normally cured for 28 days, then immersed for 7 days in a magnesium sulfate solution containing 0.5% SO_3. Using similar mortar cubes Forrester[32] found significant changes in the compressive strength of portland cements containing 9 or 5% C_3A, when immersed for 90 days in a Na_2SO_4 solution containing 3.5% SO_3.

Clearly, the strength loss measurements provide a comprehensive assessment of the deterioration of a hydrated cement paste due both to reduction of stiffness (i.e. attack on CH and C-S-H) and microcracking (i.e., excessive expansion on the ettringite formation from alumina-bearing products). However, the 3 to 4 months needed to get the test results from mortar prisms or cubes, although small in dimension, is still too long. According to Biczok,[2] Merriman had described a qualitative test for sulfate

resistance, using **neat cement paste** specimens (0.26 water/cement ratio) cured for 3 days, and thereafter suspended in a 10% solution of Na_2SO_4. Daily the sulfate content of the test solution is brought back to the original concentration by neutralizing it with sulfuric acid. This tends to accelerate the sulfate attack by a mechanism which is discussed later. At the end of the 28-days immersion, a visual estimate of the deterioration is obtained. It may be noted that due to the short curing period, the Merriman test is not applicable to blended portland cements.

To make the Merriman Test quantitative and applicable to both portland and blended portland cements, Mehta and Gjorv[33] used small cubes (12.5 mm) of high-porosity cement pastes (0.5 water/cementitious ratio), which are subjected to accelerated curing at 50°C for 7 days before immersion in a 4% Na_2SO_4 solution (2.1% SO_3). Once in every 24h period, the pH of the immer-sion solution is brought back to the original level by manual titration with 1N H_2SO_4 . Using five different types of cements, with known field performance history to sulfate attack, it was shown by the authors[33] that a 28-days immersion period was sufficient to differentiate between the good and the bad cements on the basis of the compressive strengths data before and after the immersion.

Subsequently, Mehta[34] automated the sulfuric acid titration procedure by using a pH-stat, which permits a continuous control of the pH of the immersion solution by releasing a few drops of 0.1N H_2SO_4 solution whenever the hydroxyl ion concentration of the solution goes up to indicate alkaline pH. Later, Brown[35] was able to establish conclusively that the maintenance of the pH of a sulfate solution (in which portland cement mortar specimens were immersed) at a constant and predetermined value through controlled sulfuric acid additions, ensured that the sulfate ion concentration in the solution remained invariant with time. The author compared the rates of sulfate attack both with and without the environmental control (i.e., the pH control), and reported that the environmental control significantly increased the rate of sulfate attack as measured by either strength loss or linear expansion. This is because in conventional immersion tests as a result of dissolution of CH, within a few hours after immersion of test specimens, the hydroxyl ion concentration of the solution rises from about 6-7 (which is the typical pH of a solution of technical grade Na_2SO_4) to 12-12.5. At this pH, only the ettrringite formation can occur; the gypsum formation and the C-S-H decomposition do not take place until the sulfate solution has a lower pH (e.g., 8-11.5 pH range). Since field experience with structures exposed to sulfate waters that are regularly replenished often shows the presence of gypsum and the absence of C-S-H and CH, it should be apparent that the laboratory tests involving stagnant sulfate solutions (i.e., without control of pH and sulfate concentration) are not only time-consuming but also have limited validity.

Recent work by Reardon[36] confirmed the significance of contributions by Mehta[34] and Brown[35] to the development of a suitable accelerated test for sulfate resistance. Using a chemical model, the author simulated the phase changes that occur with the progressive addition of sulfuric acid to a kg of water containing one mole each of CH, C-S-H (with Ca/Si ratio of 2.12), and C_4AH_{13}. Such a simulation is relevant to the

understanding of mineralogical changes that occur in concrete as a result of attack by atmospheric sulfur dioxide. With decreasing pH, the following order of phase changes is indicated: in the 12-12.5 pH range, CH and C_4AH_{13} (and possibly the monosulfate hydrate) dissolve and ettringite precipitates; in the 10.6 to 11.6 pH range, gypsum precipitates; at 10.6 pH, ettringite decomposes to form gibbsite and gypsum; and at 8.8 pH, C-S-H decomposes to form silica gel. The model predicts an overall decrease in the Ca/Si ratio from 2.12 at a pH of 12.5, to a Ca/Si ratio of 0.5 at a pH of 9 below which C-S-H will decompose to form amorphous silica (Fig. 2). Thus, at pH values lower than 12.5 the changes in the composition of C-S-H resulting in eventual decomposition have obvious implication to the loss of adhesion and strength of products which contain C-S-H as the principal mineral after cement hydration. Since portland-pozzolan and portland-slag cements are believed to contain C-S-H with much lower Ca/Si ratio (viz., Ca/Si ≈ 1) than hydrated portland cements, the former are inherently more stable to acidic solutions, and even to solutions in the 9 to 11 pH range (Fig. 2).

Measures for Prevention of Sulfate Attack

Assuming a situation where sulfate water cannot be prevented from coming into contact with a concrete structure, the only defense against sulfate attack would lie in the control of concrete quality, especially the permeability. High cement content, low water/cement ratio, proper compaction and curing, and control of cracking during service are among the important factors that contribute to low permeability of concrete. If cracking in service is unavoidable due to one or more of the several possible causes (such as drying shrinkage, thermal shrinkage, cycles of freezing and thawing, and corrosion of reinforcing steel), additional safeguard can be provided by the use of sulfate-resisting cements and/or mineral admixtures in concrete. On the other hand, by controlling the chemistry of cement alone it is not possible to provide long-term protection to a permeable concrete which is exposed to moderate or high sulfate concentrations, as discussed next.

With moderate conditions of sulfate attack (up to 0.2 sulfate content of soil, or up to 1500 mg/liter sulfate in water), experience shows that ASTM Type II portland cement (less than 8% C_3A) can perform satisfactorily provided the water/cement ratio of the concrete is held below 0.5. With severe conditions of sulfate attack (0.2 to 2% sulfate in soil, or 1500-10000 mg/liter sulfate in water) ACI Building Code 318 recommends the use of ASTM Type V portland cement (less than 5% C_3A), and a water/cement ratio below 0.45.

The control of C_3A content for the purpose of sulfate resistance, which was incorporated in 1940 into the ASTM C 150 Standard Specifications for Portland Cement, addresses only the problem of sulfate expansion associated with the ettringite formation. A low-C_3A cement does not eliminate the susceptibility to sulfate attack of other phases of hydrated cement paste, such as CH and C-S-H, and the subsequent loss of strength. For example, Gjorv[37] found that the flexural strength of concrete test blocks made from several portland cements, including a cement with 3% C_3A, were

significantly affected on 30 years of exposure to seawater. As discussed next, the use of portland-pozzolan or portland-slag cements offers a better solution to the overall problem of sulfate attack, and field experience seems to confirm this view.[37] Note that instead of using a portland-pozzolan or a portland-slag cement, the same purpose is served when a pozzolan or a slag is used in the concrete mixture as a partial replacement for cement.

The source of sulfate concentrations below 1500 mg/liter in groundwater may be gypsum in the soil. However, sulfate concentrations significantly larger than 1500 mg/liter are generally associated with the presence of magnesium, sodium, or potassium sulfates. Long-term field experience and accelerated laboratory tests show that under these conditions the control of C_3A content of cement alone does not offer an effective protection against the exchange reactions involving decomposition of CH and C-S-H. Since the dissolution of CH begins to take place as soon as the pH of the environment drops below 12.5, and the dissolution of C-S-H does not occur until the pH drops below 8.8, the CH is more vulnerable to sulfate attack. This is why blended cements containing a little or no CH on hydration perform better under severe conditions of sulfate attack. Examples of such cements are: calcium aluminate cement, portland blast-furnace slag cements with more than 70% slag, and portland-pozzolan cements with at least 25 percent of a highly siliceous pozzolan (such as volcanic ash, calcined clay, and low-calcium fly ash). It may be noted that, besides reducing the CH content, the incorporation of a pozzolan or slag helps to reduce the permeability of the cement hydration product by a pore-refinement mechanism.[3] It should also be remembered that normal pozzolans hydrate rather slowly and, therefore the beneficial effects from the pozzolanic reaction will not be available until a concrete mixture it has been cured for a sufficient length of time (viz, 4 to 6 weeks). Poor performance of pozzolanic or slag cements, prematurely exposed to aggressive solutions, is usually attributable to inadequate curing and not to any inherent deficiency in these cements.

Pozzolans and slags also vary widely in physical and chemical characteristics, and consequently in their ability to prevent sulfate attack. Examples described by the following paragraphs show that a proper understanding of both the mechanism of sulfate attack on concrete and the mechanisms by which pozzolans and slag improve the sulfate resistance is essential to insure a satisfactory performance of the materials selected for use in concrete.

Rosner et al[38] showed that, compared to a reference portland cement, the use of a high-calcium fly ash, irrespective of the proportions used, either failed to cause any improvement or caused a reduction in the sulfate resistance of test mortars made with blended cements. Mehta[39] used 16 different fly ashes to investigate the effect of fly ash composition on the sulfate resistance of blended cements containing a Type I portland cement (11% C_3A), and 25 or 40% fly ash. The calcium, alumina and sulfate contents of the fly ashes varied widely. When the mineralogical composition of the fly ash was such that the formation of ettringite occurred in the hydrated pastes of the blended cement even before the immersion in the sulfate solution, the blended cement

performed well in the test. On the contrary, when prior to the sulfate exposure the hydrated paste of the blended cement contained alumina-bearing phases that are known to be vulnerable to sulfate attack (viz, the monosulfate hydrate), the cement performed poorly in the test. The X-ray diffraction patterns of hydrated pastes of blended cements containing two different fly ashes are shown in Fig. 3. The cements containing Fly Ash No. 6 (which, upon hydration, formed ettrringite instead of the monosulfate hydrate) performed well in the sulfate immersion test, whereas the cements containing Fly Ash No. 10 (which, upon hydration, formed the monosulfate hydrate) performed rather poorly.

Probably for similar reasons, the sulfate resistance of portland-blast furnace slag cements is dependent on the composition of the slag and the slag content of the cement. Based on the findings of many researchers, ASTM C 989-1985 contains the following summary of the state-of-the-art on the sulfate resistance of blended cements containing ground granulated blastfurnace slag:

> *Effect of slag on sulfate resistance* - The use of slag will decrease the C_3A content of the cementing materials and decrease the permeability and calcium hydroxide content of the mortar or concrete. Tests have shown that the alumina content of the slag also influences sulfate resistance, and that high alumina content can have a detrimental influence at low slag-replacement percentages. The data from these studies of laboratory exposure of mortars to sodium and magnesium sulfate solutions provide the following general conclusions.
>
> The combinations of slag and portland cement in which the slag content was greater than 60 to 65%, had high sulfate resistance, always better than the portland cement alone, irrespective of the Al_2O_3 content of the slag. The improvement in sulfate resistance was greatest for the cements with the higher C_3A contents.
>
> The low alumina (11%) slag increased the sulfate resistance independently of the C_3A content of the cement. To obtain adequate sulfate resistance higher percentages were necessary with the higher C_3A cements. The high alumina (18%) slag adversely affected the sulfate resistance of portland cements when blended in low percentages (50% or less).

As stated before, the hydrated cement pastes containing approximately 70% slag are expected to contain a little or no free calcium hydroxide. It is the calcium hydroxide which, on sulfate exposure, contributes greatly to sulfate attack by promoting the formation of gypsum and microcrystalline ettringite. Also, the impermeability of portland-slag cement pastes increases with increasing slag content.

Stark[40] reported the results of five years of sulfate exposure of concrete specimens exposed to a sulfate-rich soil at a testing facility in Northern California. Concrete mixtures made with an ASTM Type II portland cement (4% C_3A) showed resistance to sulfate attack that was equivalent to corresponding concretes made with a Type V portland cement. Fly ash and ground granulated slag, when used as cement replacement materials, generally reduced the sulfate resistance of concrete. According to the author, a possible reason for this inconsistency in results (compared to the general experience of many other researchers) may lie in the fact that concrete prisms in the Northern California test facility are subjected to wetting and drying cycles in sulfate water, whereas most other conclusions are based on continuous immersion. It was observed that the deterioration due to sulfate attack was confined to the upper portion of the concrete prisms where drying had taken place, while the lower portion of the concrete prisms continued to remain in perfect condition. Stark[40] concluded that it was the salt weathering phenomenon (i.e. crystallization of sodium sulfate salt), rather than the classical sulfate attack (i.e. ettringite formation), which caused the concrete deterioration at the California testing facility. This shows that testing conditions must be carefully evaluated before the results from two different test methods are compared.

In conclusion, with regard to sulfate attack the anomalous behavior of pozzolan or slag cements in field or laboratory tests reported in the literature does not appear to be due to something which is inherently wrong with these cements. The anomalous behavior is usually due to the use of improper tests methods or mix proportions, or due to inadequate curing of concrete before the sulfate exposure. Only when, in some exceptional cases, the mineralogical composition of a mineral additive has been unsatisfactory, its use resulted in poor performance of the concrete on sulfate exposure.

CONCLUSIONS

Many natural and industrial waters contain sulfate ions in concentration that can be deleterious to concrete structures on long-term exposure. Effluents from fertilizer production facilities and drainage waters from heavily fertilized soils are sources of ammonium sulfate which is quite corrosive. New sources of sulfate-related corrosion in industrialized environments are the ashes and gaseous products from combustion of high-sulfur fuels. For instance, high levels of acidity in rainwater and fogs due to SO_2 and NO_x have been reported from many urban and industrial areas.

A review of case histories of deteriorated concrete in structures which have been subjected to long-term sulfate exposure shows that only permeable concretes in moist environments are vulnerable, and that the sulfate attack is seldom the sole phenomenon responsible for concrete deterioration. Microcracking of concrete, increase in permeability, and a high level of water saturation are generally preceded by

sulfate attack and other types of chemical as well as physical attacks, which result in expansion and cracking. Field experience shows that in most cases the sulfate attack manifests itself in the form of loss of adhesion and strength by the cement paste present in concrete.

Topochemical formation of ettringite with directional crystal growth, and swelling of ettringite by water adsorption are two hypotheses that have been proposed among others to explain expansion and cracking. Experimental verification of these hypotheses has been difficult because it requires the observation of processes that leave behind only the effects but not the actual causes which produced the effects. Although, under certain environmental conditions, directional crystal growth of salts form a permeating solution is known to cause expansion and cracking, it is concluded that osmotic forces involved with the swelling of poorly crystalline ettringite in concrete are probably important in sulfate expansion after the concrete has been weakened by decomposition of CH and C-S-H, as a result of sulfate attack. This hypothesis has the benefit of being more universal in the sense that it involves sulfate attack on all components of the cement paste (rather than on the alumina-bearing phases alone), and it has elements that are common to other expansive phenomena in concrete technology.

The absence of a conclusive hypothesis on mechanisms responsible for sulfate attack on concrete has prevented the development of appropriate test methods and specifications for sulfate resisting cements. For a variety of reasons, discussed in this report, the current ASTM standard test methods and specifications are not entirely satisfactory. Recent work shows that, both from theoretical and practical standpoint, immersion tests, involving continuous control of the pH of the sulfate solution, would be more suitable for adoption as accelerated laboratory tests for evaluation of sulfate resistance of cements.

A review of the measures for prevention of sulfate attack shows that control of the permeability of concrete is more important than control of the chemistry of cement. The use of a low water/cement ratio and good quality pozzolans or slags in appropriate amounts, therefore, provides a better approach to the problem of sulfate attack than the use of a sulfate resistance portland cement alone. Enough information is now available on the mineralogy and proportions of pozzolans or slags needed for long-term durability of concrete to sulfate environments.

ACKNOWLEDGEMENT

This article is being reproduced by permission of the American Ceramic Society. It was first published in the Material Science of Concrete III, edited by J. Skalny, pp. 105-129, 1992.

REFERENCES

1. F. M. Lea, The Chemistry of Cement and Concrete, Chemical Publishing Company, Inc., New York, 1971.

2. I. Biczok, Concrete Corrosion and Concrete Protection, Chemical Publishing Company, Inc., New York, 1967.

3. P. K. Mehta, Concrete: Structure, Properties, and Materials, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1986.

4. T. Thorvaldson, V. A. Vigfursson, and R. K. Larmour, "The action of sulfates on the components of portland cement", Trans. Royal Soc. Canada, 21, Sec. III, p. 295, 1927.

5. L. H. Tuthill, "Resistance of cement to the corrosive action of sodium sulfate solutions," J. Am. Concrete Inst., 33, p. 83, 1936.

6. D. G. Miller, and P. W. Manson, "Long-time tests of concretes and mortars exposed to sulfate waters," Univ. of Minnesota Agr. Exp. St. Tech. Bull. 194, 1951.

7. E. M. Harboe, "Long-time studies and field experiences with sulfate attack," Proc. George Verbeck Symp. on Sulfate Resistance of Concrete, ACI SP-77, pp. 1-20, 1982.

8. B. P. Bellport, "Combating sulfate attack on concrete on Bureau of Reclamation Projects," Proc. Thorvaldson Symp. on Performance of Concrete, Univ. of Toronto Press, pp. 77-92, 1968.

9. T. J. Reading, "Physical aspects of sodium sulfate attack on concrete," Proc. George Berbeck Symp. on Sulfate Resistance of Concrete, ACI SP-77, pp. 75-82, 1982.

10. P. K. Mehta, "Discussion on combating sulfate attack on concrete," J. ACI, Proc., Vol. 73, No. 4, pp. 237-38, 1976.

11. G. A. Novak, and A. A. Colville, "Efflorescent mineral assemblages associated with cracked and degraded residential concrete foundations in Southern California," Cement and Concrete Research, Vol. 19, pp. 1-6, 1989.

12. G. C. Price and R. Peterson, "Experience with concrete in sulfate environments in Western Canada," Proc. Thorvaldson Symp. on Performance of Concrete, Univ. of Toronto Press, pp. 93-112, 1968.